Electronics materials - Stress and its effect on materials

Introduction

You will have already seen in Mechanical properties of metals that stress on materials results in strain – first elastic strain and then, sometimes (depending on the material), plastic strain. This is shown in Figure 1.

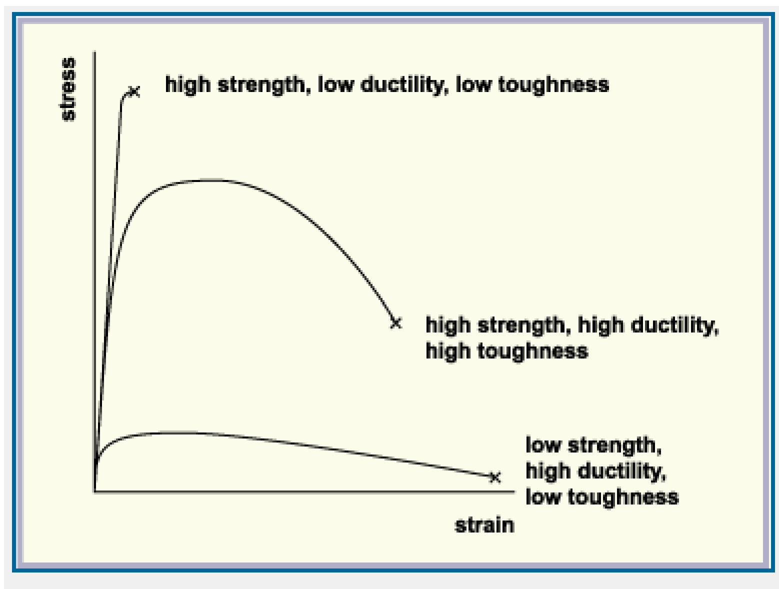

Figure 1: Typical stress-strain curves

The initial straight-line sections in each graph represent the Modulus of Elasticity (or Young's Modulus, or stiffness) of the material. If the stress is removed during this elastic strain period, the material will revert to its original shape.

However, if the load, or stress, goes beyond this linear section, we enter the area of plastic strain and the material will now never revert to its original shape. One would think that as long as we keep the stress within this linear elastic region, we would be quite safe – the material would not fail. However, this is not always the case, and we will shortly look at three ways in which materials, such as solder joints, can fail under low applied stresses. But first, let us look at the two common types of fracture, ductile and brittle.

Types of failure

Fracture is the result of an applied stress and this stress can be tensile, compressive, shear and/or torsional. There are two fracture modes possible – ductile and brittle – depending on the ability of the material to experience plastic deformation.

Obviously we do not want failures to occur. However, if they are inevitable, it is far better that we have some warning – for example a gradual change of dimension (strain) occurring in response to the stress – instead of a sudden catastrophic failure with no warning. When a material does strain significantly before failure, it will exhibit a ductile fracture.

Ductile fracture

Ductile fracture involves plastic deformation in the vicinity of an advancing crack, and is a slow process. It is stable, and will not continue unless there is an increase in the level of applied stress. It normally occurs in a trans-granular manner (across the grains) in metals that have good ductility and toughness. Often, a considerable amount of plastic deformation – including necking – is observed in the failed component. This deformation occurs before the final fracture.

Ductile fractures are normally caused by simple overloads or by applying too high a stress to the material, and exhibit characteristic surface features with a significant portion of the fracture surface having an irregular, fibrous face. They also have a small shear lip, where the fracture surface is at a 45° angle to the applied stress. The shear lip, indicating that slip occurred, gives the fracture the cup-and-cone appearance shown in Figure 2. Simple macroscopic observation of this fracture may be sufficient to identify the ductile fracture mode.

Figure 2: Macroscopic image of a ductile fracture (x29.7)

Figure 2: Macroscopic image of a

Examination of the fracture surface at a high magnification – using a scanning electron microscope (SEM) – reveals a dimpled surface. Under a normal tensile stress, these dimples (Figure 3 left) are usually round or equiaxed (having the same dimensions in all directions) – while if shear stress has been dominant, the dimples are oval-shaped or elongated, with the ovals pointing towards the origin of fracture (Figure 3 right).

Figure 3: Microscopic images of ductile fractures (x1000)

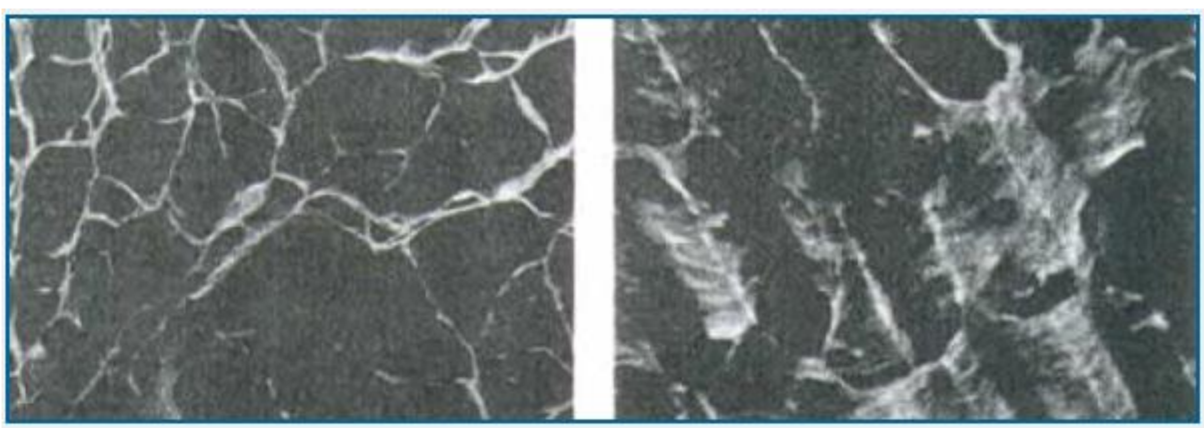

Figure 3: Microscopic images of ductile fractures (x1000)

Brittle fracture

In brittle fractures, cracks spread very rapidly, with little or no plastic flow, and are so unstable that crack propagation occurs without further increase in applied stress. They occur in high strength metals, in metals with poor ductility and toughness, and in ceramics.

Even metals that are normally ductile may fail in a brittle manner at low temperatures, in thick sections, at high strain rates (such as impact), or when flaws play an important role. Brittle fractures are frequently observed when impact rather than overload causes failure.

Brittle fracture can be identified by observing the features on the failed surface. Normally, the fracture surface is flat and perpendicular to the applied stress in a tensile test. If a failure occurs by cleavage, each fractured grain is flat and differently oriented, giving a shiny, crystalline appearance to the fracture surface (Figure 4).

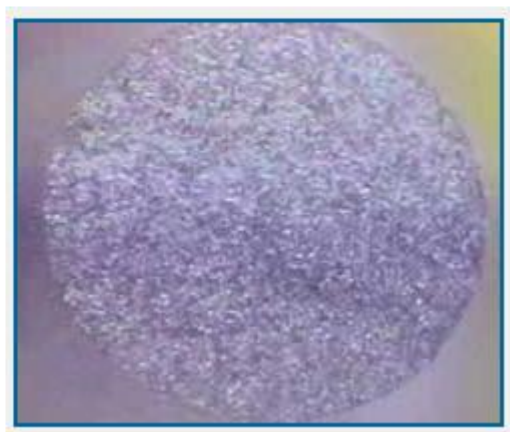

Figure 4: Macroscopic image of a brittle fracture (x6.5)

Initiation of a crack normally occurs at small flaws which cause a concentration of stress. Normally, the crack propagates most easily along specific crystallographic planes by cleavage. However, in some cases, the crack may take an inter-granular (along the grain boundaries) path, particularly when segregation or inclusions weaken the grain boundaries (Figure 5). Note that a crack may propagate at a speed approaching the speed of sound in the material!

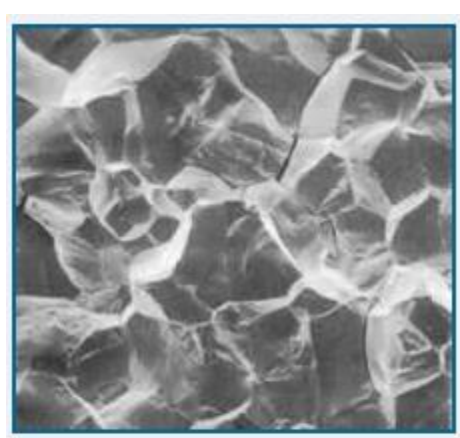

Figure 5: Microscopic image of intergranular brittle fracture (x1000)

Fatigue stresses

Fatigue is a form of failure that occurs in materials subjected to fluctuating stresses – for example, solder joints under temperature cycling. Under these circumstances, it is possible for failure to occur at a stress level considerably lower than the tensile or yield strength for a static load.

The term 'fatigue' is used because this type of failure normally occurs after a lengthy period of repeated stress cycling. It is the single largest cause of failure (approximately 90%) of metallic materials, and polymers and ceramics (other than glasses) are also susceptible to this type of failure. Although failure is slow in coming, catastrophic fatigue failures occur very suddenly, and without warning.

Fatigue failure is brittle-like in nature – even in normally ductile metals – in that there is very little, if any, gross plastic deformation associated with failure. The process occurs by the initiation and propagation of cracks, and the fracture surface is usually perpendicular to the direction of an applied stress.

A major problem with fatigue is that it is dominated by design. Whilst it is possible to assess the inherent fatigue resistance of a material, the effects of stress-raisers such as surface irregularities and changes in cross-section, as well as the crucial area of jointing (solder joints!) can be a major problem.

Failure by fatigue is the result of processes of crack nucleation and growth, or, in the case of components which may contain a crack introduced during manufacture, the result of crack growth only brought about by the application of cyclical stresses. The appearance of a fatigue fracture surface is distinctive and consists of two portions, a smooth portion, often possessing conchoidal, or 'mussel shell', markings showing the progress of the fatigue crack up to the moment of final rupture, and the final fast fracture zone. This is shown in Figure 6.

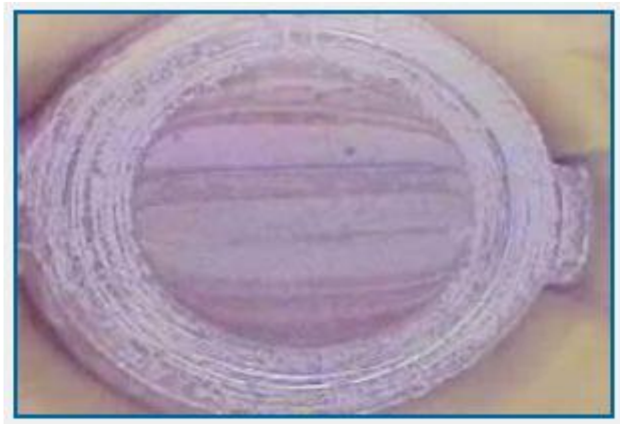

Figure 6: Macroscopic image showing fatigue beachmarks (x6.5)

The bands visible in the smooth portion, are often referred to as beachmarks. These beachmarks (so called because they resemble ripple marks on a beach) are of macroscopic dimensions – they can be observed with the unaided eye. Each beachmark band represents a period of time over which crack growth occurred.

At higher magnifications, using a scanning electron microscope, fatigue striations can be observed (Figure 7). Each striation is thought to represent the advance distance of the crack front during a single load cycle.

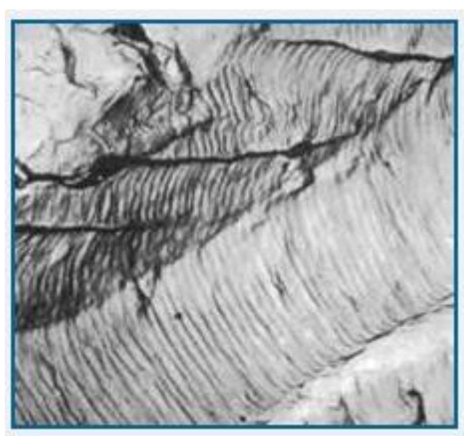

Figure 7: Scanning electron microscope image of fatigue striations (x1000)

An important point regarding fatigue failure is that beachmarks do not occur on the region over which the final rapid failure occurs. This region will exhibit either ductile or brittle failure – evidence of plastic deformation being present for ductile, and absent for brittle failure.

The number of cycles that a component can survive without failure depends on the stress amplitude applied. Obviously, the greater the stress amplitude the lower the number of cycles to failure and this is reflected in Figure 8 which exhibits the "Stress amplitude – Number of cycles to failure (or S-N) curve" typical of non-ferrous materials such as solders.

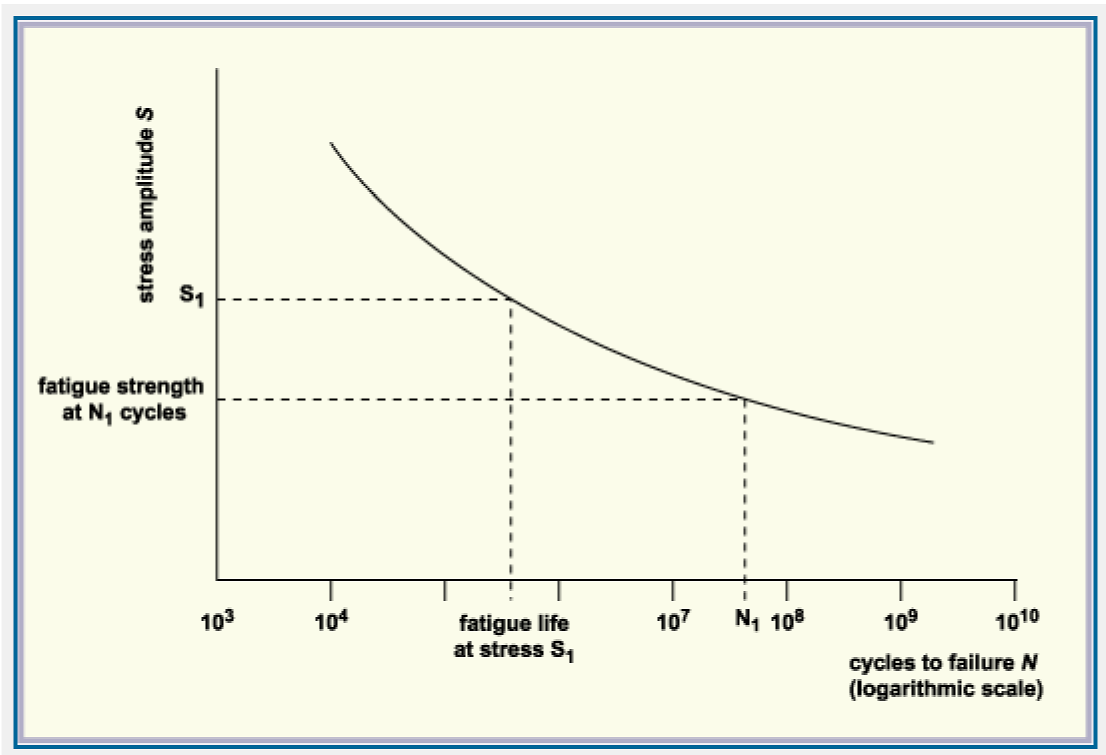

Figure 8: S-N curve for non-ferrous materials such as solders

The fatigue strength is the maximum permitted stress amplitude for a given number of cycles. The fatigue strength of a solder joint is always less than the fatigue strength of the basic material. This is because it is determined by:

- the size and distribution of defects within the solder alloy and
- the magnitude of the stress concentration factor at the junction of the solder alloy and the parent metal.

This important topic will be examined more closely later.

Corrosion fatigue is the development and propagation of cracks in a material that is subjected to alternating or fluctuating cycles of load. The presence of a corrosive environment will accelerate the formation and growth of fatigue cracks, thus reducing the fatigue life of the material.

Creep

Materials are often placed in service at 'relatively high temperatures' and exposed to static mechanical stresses. These stresses are less than the yield strength of the material but nevertheless can cause plastic deformation to take place – particularly over a long period of service time. This phenomenon is known as creep. Note that the term 'relatively high temperatures' means high homologous temperatures (Tservice/Tmelting) and is a measure of how near the temperature is to the melting point of the material concerned, as shown in Figure 9 of Mechanical properties of metals.

So room temperature (20°C) is a low homologous temperature for steel (melting point around 1600°C), but is a high homologous temperature for tin-lead solder (melting point around 180°C).

Creep is observed in all material types – in metals it only becomes important at temperatures greater than about 0.4Tm (where Tm is the melting point in Kelvin). Soft metals such as tin and lead creep at room temperature while aluminium and its alloys creep around 250°C. Steel creeps at about 450°C while nickel-based alloys (nimonics) creep at around 650°C. A typical creep curve is shown in Figure 9.

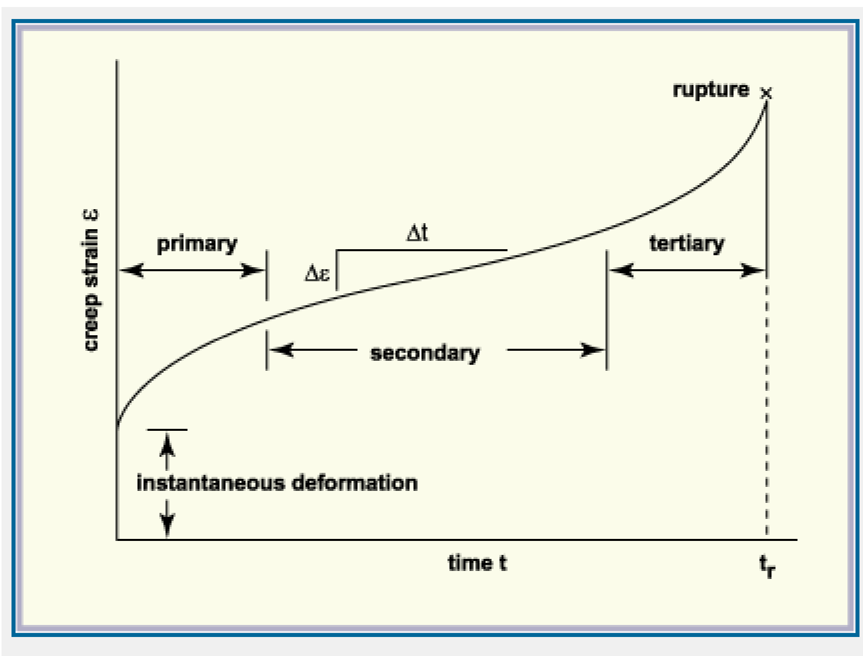

Figure 9: Creep strain versus time graph

The temperature and length of service determines whether or not creep must be considered as a possible mode of failure for a given material component. For example one particular aluminium-copper alloy was used for the forged impellers in the jet engine for the Gloster Meteor aircraft. In this application, the temperature of operation was up to 200°C and the stress was high enough to limit the life to a few hundred hours. Clearly, in this case, 200°C is a creep-producing temperature. The same alloy is used as the skin for Concorde, and over most of this structure the temperature does not exceed 120°C. However, the Concorde airframe is designed for a life in service of 20,000–30,000 hours, and this is a long enough period for 120°C to constitute a possible hazard. Creep is thus important in both applications, even though the temperatures are different.

Combined creep and fatigue

Since neither fatigue nor creep while acting on their own is fully understood, the mechanisms involved when they act together are even less well understood. However:

- There is evidence of a synergistic relationship i.e. the sum of their joint effects is greater than their individual contributions

- Factors of little importance to fatigue at room temperature – such as frequency, wave shape and recovery – can become important at high temperatures. Similarly, the mode of failure alters from transcrystalline to intercrystalline

- Uneven heating can lead to thermal fatigue, while oxidation and corrosion result in degradation of creep and fatigue resistance.

Stress raisers

Fatigue and creep are two modes of low stress failure. A third mode of failure is caused by the presence of 'stress raisers'. First investigated by Griffiths in the 1920s, these are microscopic flaws or cracks which always exist, both on the surface and internally, and result in an amplification or concentration of the applied stress at the crack tip. In service, the stress concentrators of importance are crack-like defects and examples include:

- discontinuities in soldered joints, and

- cracks which have grown by fatigue or stress-corrosion mechanisms.

It is usually possible to detect such defects, using ultrasonic inspection or radiography, to determine the maximum size of defect in the region of interest.

At positions far removed from cracks, the stress is just the nominal stress, that is, the load divided by the cross-sectional area, and this does not pose a problem if the applied stress is below the elastic limit. However, in the vicinity of small cracks or flaws, the situation can be serious. Because of their ability to amplify an applied stress in their locale, such flaws are called 'stress raisers'.

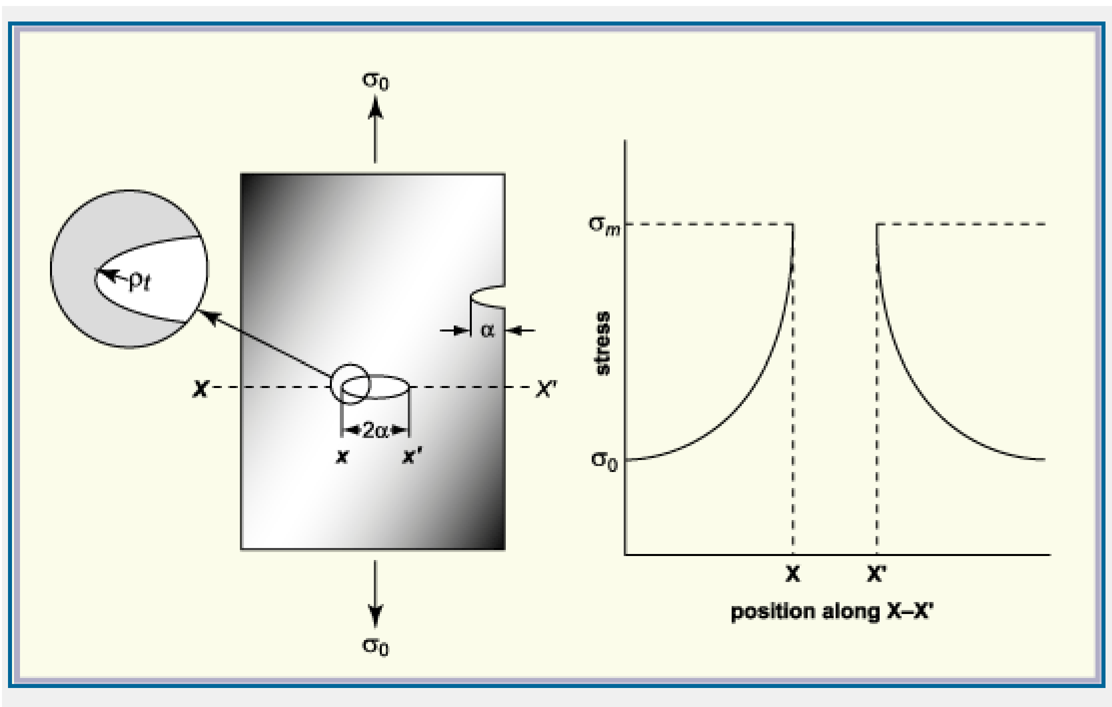

Figure 10: Schematic representation of stress-raising defect

With reference to Figure 10, the maximum stress at the crack tip, sm may be approximated by:

$$\sigma_m = 2\sigma_o \cdot \sqrt{\frac{a}{\rho_t}}$$

where so is the applied stress, rt is the radius of curvature of the crack tip and a represents the length of a surface crack or half the length of an internal one. The ratio sm/so is termed the stress concentration factor Kt and is a measure of the degree of stress amplification at the tip of a small crack. While hairline cracks (with a large length to crack tip ratio) are most undesirable, stress amplification also occurs on a macroscopic scale, for example, sharp corners in solder joints.

The effects of stress raisers are more significant in brittle than in ductile materials. In ductile materials, plastic deformation allows a more uniform distribution of the stress in the vicinity of the stress raiser and the resultant stress concentration factor is appreciably less than those in brittle materials.

In the 1920s, Griffith proposed that fracture occurs when the theoretical cohesive strength is exceeded at the tip of one of the numerous flaws existing in most materials. If no flaws were present the fracture strength would be equal to the cohesive strength of the material. Very small, virtually defect-free metallic and ceramic whiskers have been grown with fracture strengths approaching theoretical values.

In many engineering situations where there is a measure of cyclical stressing (including electronic solder joints), we must be aware that tiny, sub-critical cracks can grow and become critical. Fast fracture will then occur.

Author: Martin Tarr

Source: http://www.ami.ac.uk/courses/topics/0124_seom/index.html